Innovations in Teaching with Computers: What Works, What Doesn't, and How We Can Tell

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Session A6:
Computational Physics in Research and Teaching: GRC Topics and Themes

Gordon Research Conference series
Physics Research and Education

2000: Statistical and Thermal Physics
Jan Tobochnik and Harvey Gould

2002: Quantum Mechanics
Beth Ann Thacker

"Just what *is* a wave function?"

2004: Classical Mechanics and Non-linear Dynamics
Harvey S. Leff and David P. Jackson

2006: Electromagnetism
Stamatis Vokos and Kerry P. Browne

2008: Computation and Computer-based Instruction
Bradley S. Ambrose and Wolfgang Christian

2010: Experimental Research and Laboratories in Physics Education
Chandralekha Singh and Enrique J. Galvez

Computers in physics education:
Ongoing challenges, new opportunities

As physics instructors, we believe that effective incorporation of computation can help us:

- Motivate and excite our students to pursue physics
- Increase the likelihood of students becoming involved in research
- Enhance the connections students make between the physics and mathematics *(student-coded simulation and computer modeling)*
- Enhance student learning by allowing them to “observe” what normally is not observable *(visualization)*
- Enhance learning by freeing student time and attention to promote productive sense-making

Computers in physics education:

Ongoing challenges, new opportunities

Incorporating computation is a multi-faceted question…

Some "macro" issues:

- Devise new course(s) or revitalize existing courses?
- Devise new program/emphasis/major or revitalize existing ones?
- "Teach the algorithms" or "teach the tools"?

Some "micro" issues:

- Programming: Have students write code or modify existing code?
- Simulations: Open-ended or more restricted? How much guidance?

2007 AAPT Topical Conference on Computational Physics (W. Christian, chair)

2008 GRC theme issue articles (*Am. J. Phys.* **76**) by Chonacky and Winch; Landau; Cook; and McIntyre, *et al.;* Chabay and Sherwood; Tobochnik and Gould

Computers in physics education:

Ongoing challenges, new opportunities

Physics education research (PER) has provided deep insight into "what works" and "what does not work."

Joe Redish's appraisal* of a "cookbook lab" in which the data was collected, analyzed, and graphed by a PC:

"This is what I call a **'the computer gets an A the student gets an F'** experiment. If you didn't understand it before you saw it, you wouldn't learn much from it."

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* E. F. Redish, *Computers in Physics* **7,** 613 (1993).

Some lessons learned from physics education research*

1. Students must be intellectually engaged to develop a <u>working knowledge</u> (McDermott: *functional understanding*) of physics.

2. Nature of students' initial conceptions must be taken into account for meaningful learning to occur:

   – Specific difficulties (concepts, reasoning skills, connections between physics and formalism) must be addressed *explicitly* and *repeatedly.*

   – Traditional instruction, even in advanced topics, does not necessarily address difficulties with basic concepts.

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* L. C. McDermott, "Oersted Medal Lecture 2001: Physics education research—the key to student learning," *Am. J. Phys.* **69,** 1127 (2001);
Teaching Physics with the Physics Suite, E. F. Redish, Chap. 1 – 3 (Wiley, 2003).

Some lessons learned from physics education research*

3. Successful completion of standard quantitative problems is <u>not</u> a sufficient criterion for assessing understanding.
    - Questions that require verbal explanations of reasoning must be included as part of formative or summative assessment.

4. Student conceptions about "what it means to learn physics" affect *what* and *how* students learn.

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* L. C. McDermott, "Oersted Medal Lecture 2001: Physics education research—the key to student learning," *Am. J. Phys.* **69,** 1127 (2001);
Teaching Physics with the Physics Suite, E. F. Redish, Chap. 1 – 3 (Wiley, 2003).

Focus for this presentation

Two general questions:

- How are lessons that we have learned about student learning being implemented?
- What new lessons are we learning?

⇒ *when students are doing the coding or calculating?*

⇒ *when students instead use interactive visualizations, simulations, or virtual labs?*

Engaging students in computational modeling

At introductory level and beyond

How lessons about student learning are being implemented:

- Modeling strategies help elicit the understandings and intuitions that students use (and do not use)
- Modeling encourages active engagement and can foster productive conceptual development

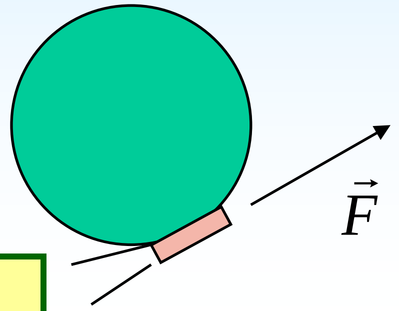
And new questions that have arisen:

- **How much guidance** do students need to develop, test, and revise productive physical models?
- To what extent does the **choice of scope** of computational activities affect student outcomes?
- Under what conditions do students **value** computation as a learning tool (rather than regard it as "just another assignment")?

Example of computational modeling

Computational lab in introductory mechanics*

Physical situation: Disk-shaped spaceship initially at rest moves under the influence of a constant force by thruster on its rim. †



Task (3-hr computational la

- Predict center-of-mass motio
- Generate mathematical expressions that govern motion of ship
- Translate expressions to code (VPython)
- Observe results (graphic) for center-of-mass trajectory
- Account for differences between output of program and their initial predictions in terms of relevant physical principles

Teaching strategy well-tested by PER

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* Buffler, et al., *Am. J. Phys.* **76,** 431 (2008). Adapted from slide by M. Haugan (GRC 2008).

† Based on problem discussed by Dudley and Serna, *Am. J. Phys.* **73,** 500 (2005).

Results from PER in rigid-body dynamics

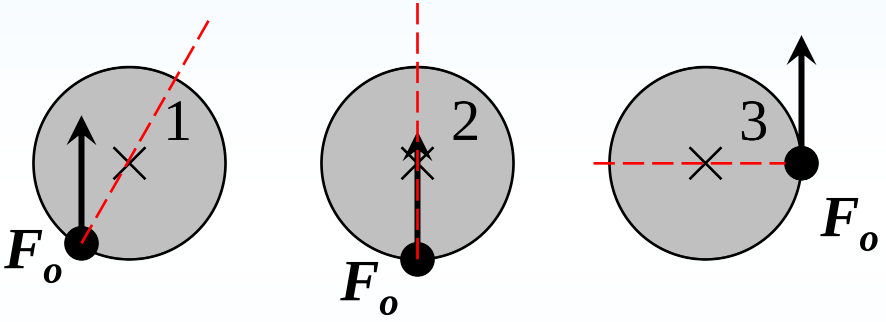
Task from "think-aloud" interviews and course exams:*

Three identical pucks (1 – 3) are at rest on a flat, frictionless ice rink. Forces of equal magnitude F_o and direction are exerted on each puck.

A. For each, show directions of (i) α and (ii) $\boldsymbol{a}_{\mathbf{CM}}$.

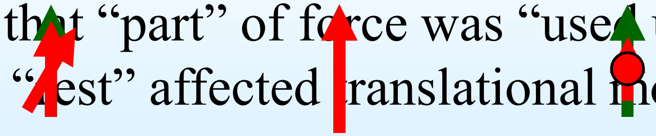
B. Rank pucks according to (i) $|\alpha|$; (ii) $|\boldsymbol{a}_{\mathbf{CM}}|$.

Explain your reasoning in each case.



Correct answers for a_{CM}:

Common difficulty: Incorrect belief that "part" of force was "used up" for rotation and the "rest" affected translational motion



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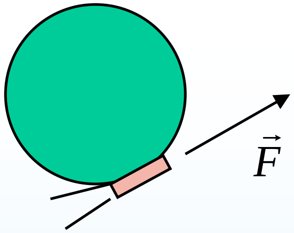
* Research underlying "Dynamics of rigid bodies" from *Tutorials in Introductory Physics* by McDermott, Shaffer, and Phys. Ed. Group at UW (Prentice-Hall, 2002).

Student predictions before coding

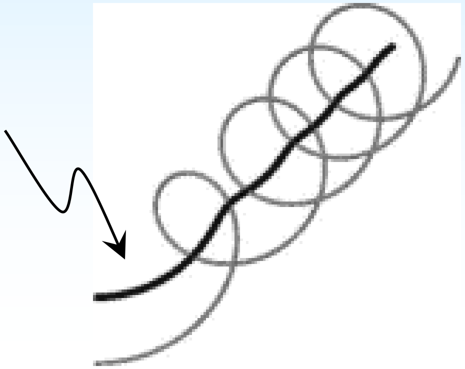
Computational lab in introductory mechanics*

Predicting path of COM *before* coding simulation



Qualitatively correct path:

(COM = black curve)



None (0/51) correct

Common incorrect predictions:

Most (but not all) successfully generated correct code for simulation by the end of lab

Most students (45/51) responses reflected correct intuition that ship would rotate <u>and</u> translate

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* Buffler, et al., *Am. J. Phys.* **76,** 431 (2008).

Quality of student reflection after modeling

Computational lab in introductory mechanics*

- About half of class gave **little or no indication** of (dis-)agreement
- About another 25% (14/51) indicated (dis-)agreement only on basis of **surface features**

  > "I predicted [the ship] would move in a circle, but the actual result is a wavey curve which eventually becomes straight."

- The rest (11/51) based comparisons on elements of a **physical model**

  > "No, … we didn't take into account how the constantly increasing momentum would decrease the effect of the force when pointed in the opposite direction."

Meaningful reflection requires carefully tuned questions

Were students focused solely on coding?

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* Buffler, et al., *Am. J. Phys.* **76,** 431 (2008).

Mindsets of students engaged in calculation

Case studies in advanced courses (U. Maryland)*

Context: Videotaped collaborative work (~ 100 hrs) on homework problems

~ 10% show students using symbolic calculators

Question: How does the use of symbolic calculators affect students' decision-making in solving problems?

Observations:

Students often "drilled down into a calculation" rather than make useful (or potentially useful) connections between math and physics.

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* Bing and Redish, *Am. J. Phys.* **76,** 418 (2005).

Mindsets of students engaged in calculation

Case studies in advanced courses (U. Maryland)*

Task: For identical particles in arbitrary stationary states of a 1-D infinite well, use MATHEMATICA to calculate:

$$\left\langle \left(x_1^2 - x_2^2 \right) \right\rangle = ?$$

What some students did:

Used MATHEMATICA several (5!) different ways to try to calculate:

$$\left(\frac{2}{L}\right) \boxed{\int_{-\infty}^{\infty}} x^2 \sin^2\left(\frac{n\pi x}{L}\right) dx$$

Difficulty infusing physics into math

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* Bing and Redish, *Am. J. Phys.* **76,** 418 (2005).

Mindsets of students engaged in calculation

Case studies in advanced courses (U. Maryland)*

Task: Use Feynman-Hellmann theorem, with $\lambda = \omega$, to find $\langle V \rangle$ for 1-D simple harmonic oscillator.

$$\frac{\partial E_n}{\partial \lambda} = \left\langle \psi_n \left| \frac{\partial H}{\partial \lambda} \right| \psi_n \right\rangle, \text{ with } \lambda = \omega \qquad \Rightarrow \qquad \langle V \rangle = ?$$

Expected solution:

Extract physics from math

Recognize that $\boxed{\frac{\partial H}{\partial \omega}} = m\omega x^2 = 2\sqrt{\frac{m}{k}}\left(\frac{1}{2}k\boxed{x^2}\right) = 2\sqrt{\frac{m}{k}}\boxed{V(x)}$

and $\frac{\partial E_n}{\partial \omega} = \hbar\left(n + \frac{1}{2}\right)$ and combine.

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* Bing and Redish, *Am. J. Phys.* **76,** 418 (2005).

Mindsets of students engaged in calculation

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Task: Use Feynman-Hellmann theorem, with $\lambda = \omega$, to find $\langle V \rangle$ for 1-D simple harmonic oscillator.

$$\frac{\partial E_n}{\partial \lambda} = \left\langle \psi_n \left| \frac{\partial H}{\partial \lambda} \right| \psi_n \right\rangle, \text{ with } \lambda = \omega \qquad \Rightarrow \qquad \langle V \rangle = ?$$

What some students did instead:

Used MATHEMATICA to “brute-force” calculate both sides of above equation, obtaining:

$$"\hbar\left(n + \frac{1}{2}\right) = \hbar\left(n + \frac{1}{2}\right)"$$

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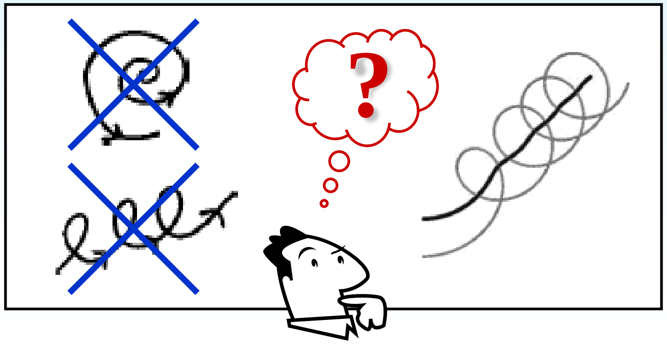
* Bing and Redish, *Am. J. Phys.* **76,** 418 (2005).

New lessons learned when students engage in computation

- Students need guidance and practice **extracting physical meaning from** results of computation.



- Students can experience obstacles **infusing physical meaning into** computational work.

$$\boxed{\int_{-\infty}^{\infty}} x^2 \sin^2\left(\frac{n\pi x}{L}\right)dx$$

Just as the mathematical formalism of physics can pose barriers to student learning, computational work can pose similar barriers.

Engaging students through virtual labs and interactive simulations

Examples presented at GRC:

- ▶ Virtual labs (*e.g.*, THERMOLAB, Virtual Experiments Electricity)
- ▶ Physics Education Technology (PhET) Project (Univ. Colorado)
- ▶ Quantum Interactive Lecture Tutorials (Univ. Pittsburgh)

Singh,
Am. J. Phys. **76** (2008)

McKagan *et al.*,
Am. J. Phys. **76** (2008)

THERMOLAB,
referenced in Zacharia
and Constantinou,
Am. J. Phys. **76** (2008)
(Sim adapted from
original by A. Huber,
Ludwig-Maximilians-
Universität Munich)

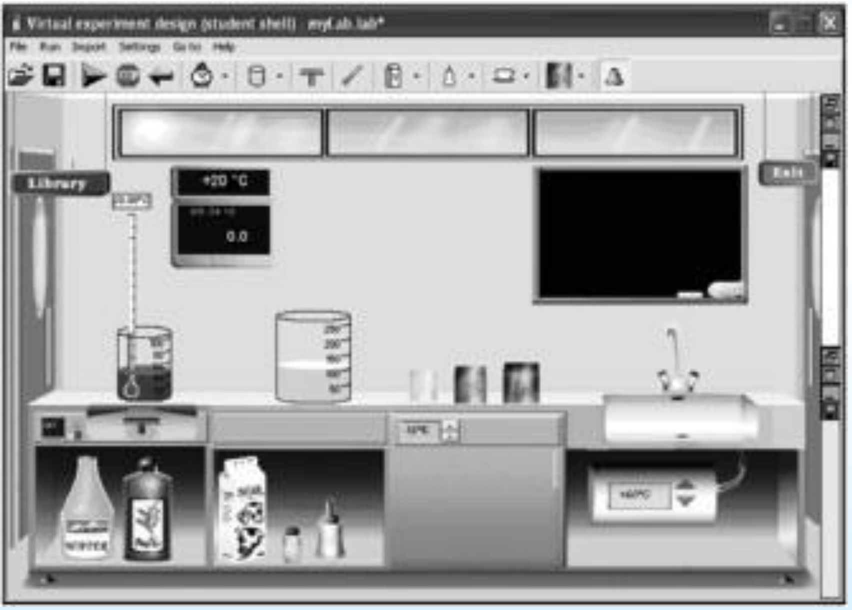
How are lessons tha *g*

What new lessons

Designing and testing virtual inquiry labs

Implementing lessons about student learning

Research goal: Measure effect on student conceptual learning when using *physical* or *virtual inquiry-based experiments* (PIBE vs. VIBE), or various combinations of both*



Co *quiry*

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* Zacharia and Constantinou, *Am. J. Phys.* **76,** 425 (2008);
Zacharia, *J. Comp. Asstd. Lrng.* **23,** 120 (2007).

† *Physics by Inquiry Vols. I & II*, by McDermott and UWPEG (Wiley, 1996).

Probing conceptual learning from virtual inquiry labs

*Research questions:**

1. Must students physically manipulate variables for meaningful conceptual learning to occur?
    - PIBE modified to duplicate faster manipulation of VIBE
2. Can conceptual learning with VIBE exceed that with PIBE?

Research methods: Pre- and post-instruction diagnostics †

- Quantitative analysis of scores
- Phenomenographic analysis of student reasoning patterns

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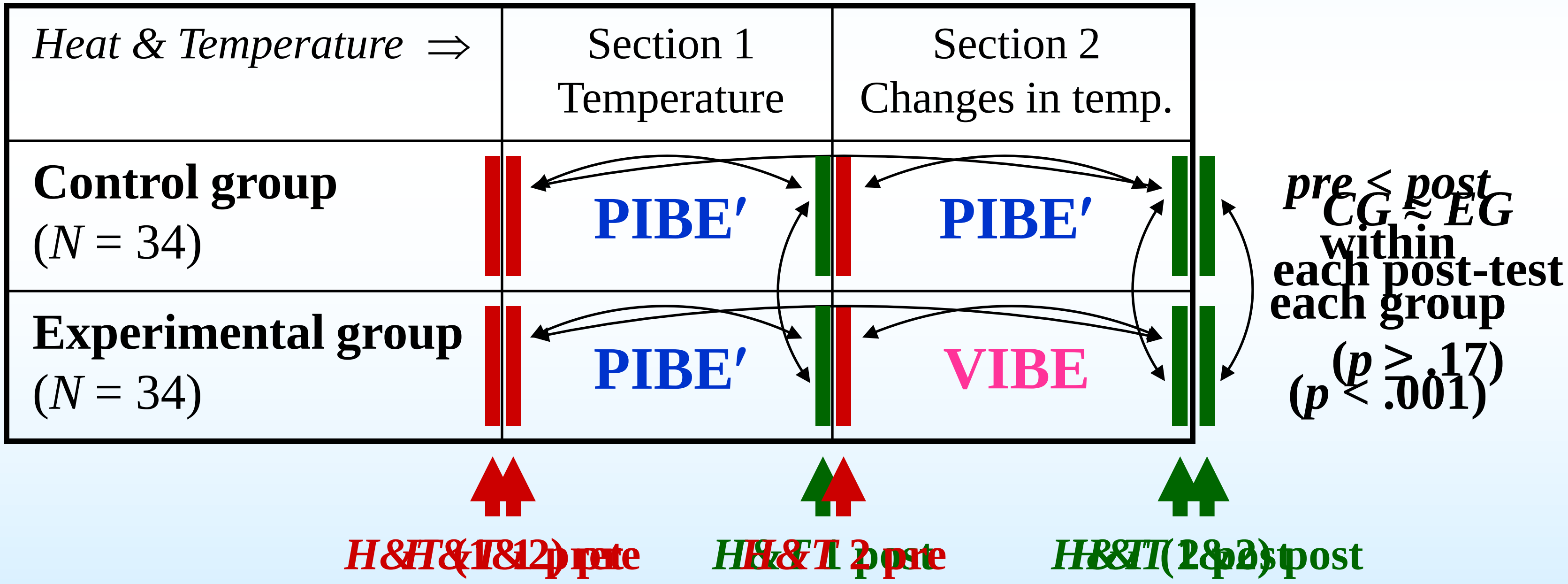
* Zacharia & Constantinou, *AJP* **76,** 425 (2008); Zacharia, *J. Comp. Asstd. Lrng.* **23,** 120 (2007).

† Developed by Phys. Ed. Group at Univ. of Washington

Probing conceptual learning from virtual inquiry labs

Q: Must students physically manipulate variables?*

⇒ **PIBE′** modified to duplicate faster manipulation of **VIBE**



Heat & Temperature ⇒	Section 1 Temperature	Section 2 Changes in temp.
Control group (N = 34)	**PIBE′**	**PIBE′**
Experimental group (N = 34)	**PIBE′**	**VIBE**

pre* < *post
within
each group
(p < .001)

CG* ≈ *EG
each post-test
(p ≥ .17)

***H&T* 1 pre**
***H&T* (1&2) pre**

***H&T* 1 post**
***H&T* 2 pre**

***H&T* 2 post**
***H&T* (1&2) post**

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* Zacharia and Constantinou, *Am. J. Phys.* **76,** 425 (2008);
Zacharia, *J. Comp. Asstd. Lrng.* **23,** 120 (2007)

Probing conceptual learning from virtual inquiry labs

Q: Can conceptual learning with **VIBE** exceed that with **PIBE**?

⇒ Faster manipulation of **VIBE** preserved

Heat & Temperature ⇒	Section 1 Temperature	Section 2 Changes in temp.
Control group (*N* = 36)	**PIBE**	**PIBE**
Experimental group (*N* = 36)	**PIBE**	**VIBE**

***H&T* 1 post**

CG* ≈ *EG

***H&T* 2 post**

***H&T* (1&2) post**

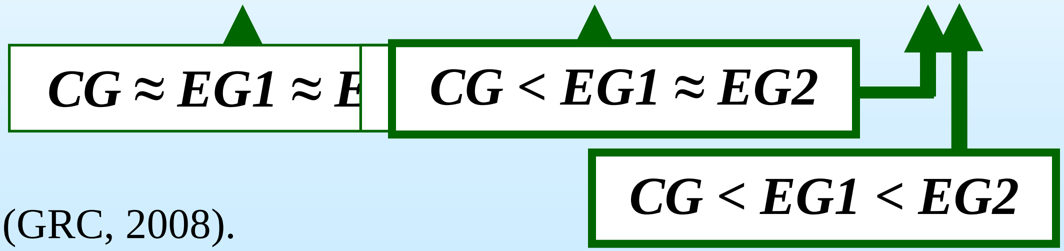
CG* < *EG

Adapted from slide by Zacharia (GRC, 2008).

Probing conceptual learning from virtual inquiry labs

Q: Do improved conceptual gains attained by **VIBE** persist even after returning to **PIBE**?

Electric Circuits ⇒	Part A Simple circuits	Part B Curr. & resist.	Part C Voltage
Control group ($N \approx 40$)	**PIBE**	**PIBE**	**PIBE**
Experim. group 1 ($N \approx 40$)	**PIBE**	**PIBE**	**VIBE**
Experim. group 2 ($N \approx 40$)	**PIBE**	**VIBE**	**PIBE**



CG ≈ EG1 ≈ E

CG < EG1 ≈ EG2

CG < EG1 < EG2

Adapted from slide by Zacharia (GRC, 2008).

New lessons learned from investigations of virtual guided inquiry

In context of guided inquiry lab-based courses:

- Physicality of manipulatives less important than their manipulation
- Incorporating full features of virtual experimentation can significantly increase conceptual gains
  - Size of gains from virtual experimentation may be context-dependent (and hence depend on nature of specific conceptual difficulties)

New questions arise, such as:

- Can virtual inquiry labs help enhance acquisition of reasoning skills and/or laboratory skills?
  - Students have difficulty using appropriate control of variables reasoning (Boudreaux, et al., *AJP* **76,** 173 (2008)).

New lessons learned while designing sims

Promoting interactivity seems to be a balancing act

Guided questioning seems necessary to engage students at a sufficiently deep level.

- Students may tend to “play” in the negative sense.
- *Predict-observe-explain* strategy requires students to be aware of, articulate, and revise their thinking.

And yet at the same time…

“Strongly guided” questions can negatively affect student mindsets.

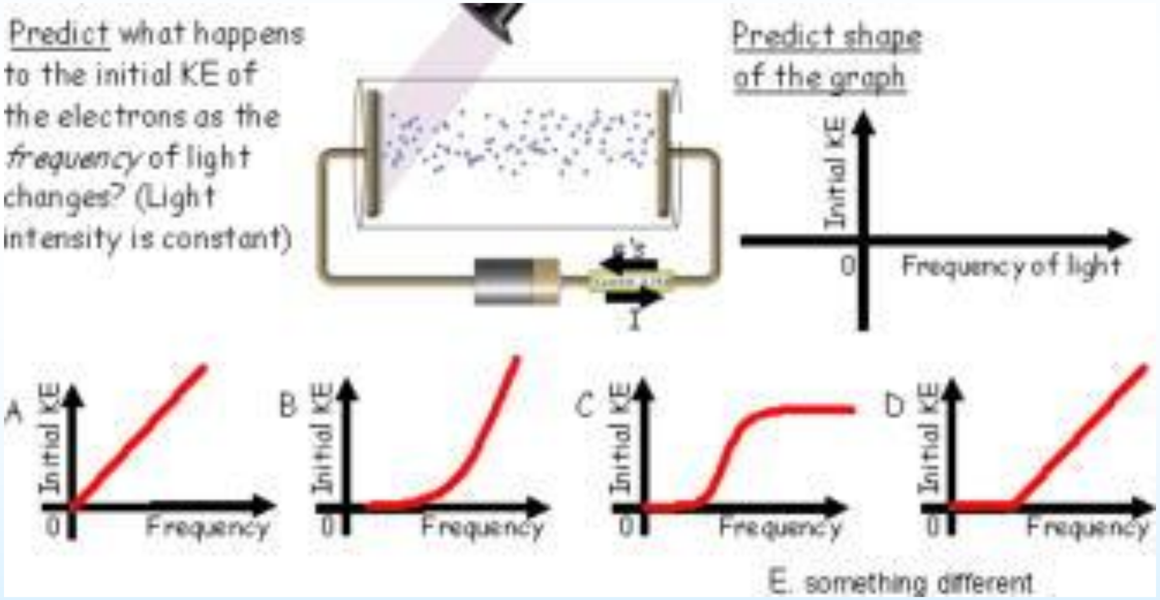
- Students may tend <u>not</u> to “play” in the <u>positive</u> sense.
- Simulations with more open-ended questions seem to encourage deeper exploration and sense-making.

Developing effective interactive simulations

Implementing lessons about student learning

1. Instructional strategies *(predict-observe-explain)* that address known student difficulties* identified by PER

From PhET simulation
Photoelectric effect
(McKagan, et al.)



Predict what happens to the initial KE of the electrons as the *frequency* of light changes? (Light intensity is constant)

Predict shape of the graph

E. something different

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* Steinberg, et al., *Am. J. Phys.* **64,** 1370 (1996); McKagan, et al., *ibid*. **77**, 87 (2009).

Developing effective interactive simulations

Implementing lessons about student learning

2. Iterative cycle of development and in-depth interviews with volunteers from intended student population*
    - Opportunities for misinterpretation are minimized?
    - Explorations are open-ended but not too intimidating?
    - Varying levels of complexity?
3. Extensive assessment through care
    - Tasks require students to demonstrate
    - Post-tests similar—not identical—to

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* Singh, *Am. J. Phys.* **76,** 400 (2008); Weiman, et al., *ibid.* **76,** 393 (2008).

† McKagan, et al., *ibid.* **76,** 406 (2008).

Summary

Evidence from physics instruction continues to demonstrate how computation can be effectively incorporated into the curriculum.

Computer modeling, virtual labs, and interactive simulations:

- Can motivate and engage students intellectually
- Can help make observable what normally is not
  - Students can “see” systems difficult or impossible to observe
  - Instructors can gain new insight into student conceptions and intuitions
- Can significantly enhance student learning
  - Explanations of reasoning necessary for meaningful model-building and meaningful assessment
  - Successful coding *not* sufficient criterion for student understanding

Summary

Recent innovations in incorporating computation into the physics curriculum have also motivated new issues and questions.

- Student **expectations** (about learning physics, in general) and student **mindsets** (during in-class activities or other assignments, in particular) can influence learning outcomes.
  - “Doing physics via computer modeling” *vs.* “programming”
- How can computation be used to go beyond conceptual learning?
  - Connecting *mathematics* ⇔ *physics*, and *theory* ⇔ *experiment*
  - Building conceptual framework upon central principles
- What **evidence** is needed to accurately and reliably measure these outcomes?

Special acknowledgements

(and a shameless plug)

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- APS Forum on Education (FEd),
  APS Division in Computational Physics (DCOMP)

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Experimental Research and Laboratories in Physics Education

Mount Holyoke College, June 6 – 11

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